Assessing the Needs for Space Reactor Standards

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A U.S. governmental interagency space reactor standards working group (SWG) was convened to address the limited availability of voluntary consensus standards currently in place specifically for space nuclear reactor design and safety. The SWG focused on reviewing existing standards, assessing agency needs, specifying gaps that could be addressed by new standards, and prioritizing those gaps through consensus group deliberations. The SWG identified a series of findings and recommendations relative to the development of space reactor standards, including moving three specific high-priority gap items to be pursued through a consensus standards development process: Safety and Risk Analysis Methods for Space Reactors, Testing Requirements for Space Reactors, including Facility Requirements, and Safe Operating Practices for Space Reactors.

I. BACKGROUND

The past few years have seen a growing interest in proposals for nuclear fission surface power on the Moon and Mars, along with nuclear thermal or nuclear electric propulsion for Mars missions, deep space exploration and other activities. Recent developments include a variety of different entities interested in space nuclear systems, accompanied by a high degree of collaboration developing among both government agencies and commercial entities. Government agencies continue to contract with the private sector to support government missions, while commercial interest in space is increasing rapidly in areas of *in situ* resource utilization, communications, and even space tourism.

The assortment of agencies and non-governmental entities potentially participating in the development of space fission reactor systems leads to differences in interests and development needs. Therefore, it is appropriate to consider whether consensus technical standards can guide future reactor development and provide consistency in the treatment of safety across different entities. To address this question a standards working group (SWG) was tasked to explore whether consensus standards activities should be pursued. The seven agencies involved were the Department of Defense (DOD), the Department of Energy (DOE), the Department of State (DOS), the Department of Transportation (DOT) represented by the Federal Aviation Administration (FAA), the Environmental Protection Agency (EPA), the National Aeronautics and Space Administration (NASA) and the Nuclear Regulatory Commission (NRC). The primary tasking for the SWG was to:

…complete a study to validate the need for such standards, address any concerns that you might have, and chart a path forward.

The SWG reviewed existing standards, assessed agency needs, specified gaps that could be addressed by new standards, and prioritized those gaps through group deliberations. Its scope was limited to space nuclear fission reactors, and thus it explicitly did not address radioisotope power or heating systems, nor did it address fusion or hybrid reactors. Further, these discussions were not tied to any currently planned missions. Another premise of the study was that standards take time to develop and should not be on any critical path for a mission. If, and when any standards are approved, then subsequent missions could implement them.

I.A. Role of Consensus Standards

With a variety of organizations considering the use of space reactors and few space reactor-specific processes currently in place, it is appropriate to consider how consensus standards may be utilized in a variety of ways, including reactor design, safety analysis, and operations. For example, National Security Presidential Memorandum 20 (NSPM-20) outlines the steps for separate launch approval chains, depending on the sponsoring agency or commercial entity requesting approval.[1] For government launches of space fission reactors, the head of the sponsoring agency approves the launch unless it falls in a category requiring White House approval, e.g., a fission reactor using highly enriched uranium (HEU). The sponsoring agency shall request of the NASA Administrator that the Interagency Nuclear Safety Review

Board (INSRB) perform a review. For commercial launches, the DOT has approval authority. NSPM-20 allows DOT to request assistance from other agencies in reviewing the safety analysis or to request an INSRB review.

One of the goals of NSPM-20 was to reduce the uncertainty in the launch approval processes for the benefit of mission planners who choose to use nuclear systems. However, NSPM-20 does not specify how the supporting analyses are to be carried out. The development of consensus technical standards can alleviate this problem, and further the goals of NSPM-20, by ensuring that the safety assessments performed by the system developers will ultimately be accepted by the sponsoring or regulating agency. Such standards will also help mission planners more accurately predict costs associated with safety assessment and launch approval.

Nuclear power is unique in that, when an accident occurs, the entire nuclear industry experiences long-term consequences, even in cases with minimal public radiological health impact, such as the accidents at Three Mile Island or the Fukushima Daiichi nuclear power plant. In that sense, each agency has a stake in the nuclear activities of other agencies. In addition, there are several areas where one agency or commercial entity may leverage the capabilities of another, including test facilities, fuel and component manufacturing, and launch facilities. Such collaboration could be simplified and can expedite the process if all entities work toward similar standards. Therefore, it is advantageous to bring together a broad range of nuclear experts to ensure that both government and commercial entities use common best practices in safety design and risk assessment.

Office of Management and Budget (OMB) Circular A-119 (Ref. 2) directs agencies to "use standards developed or adopted by voluntary consensus standards bodies rather than government-unique standards, except where inconsistent with applicable law or otherwise impractical." Each agency has appointed a senior executive to coordinate standards activities within the agency. Memorandum M-12-08, *Principles for Federal Engagement in Standards Activities to Address National Priorities*, specifies objectives for federal participation in standards activities.[3]

I.B. Relevant Available Standards

Dozens of consensus technical standards exist for terrestrial nuclear systems and handling of nuclear materials that have been developed by the American Nuclear Society (ANS), the American Society of Mechanical Engineers (ASME), the Institute of Electrical and Electronics Engineers (IEEE), American Society for Testing and Materials (ASTM) International, and others over several decades. These standards address topics ranging from materials and structures to reactor design and risk analysis methods and operations. In addition, there are many internal standards and guides produced by government agencies dealing with space launch and operations, nuclear issues, radiological preparedness and response, control of radiological air emissions, and used fuel management. SWG members provided lists of relevant documents from each agency. These lists will be made available to standards bodies as useful reference material.

It is neither practical nor appropriate to reproduce this same set of standards for space systems. While the standards for terrestrial reactors contain much useful information, the standards were not written for space systems and, in many cases, internal agency standards are sufficient to address safety issues. The foundation for potential new standards may lie in the techniques previously developed by the DOE and its laboratories for launch approval of radioisotope systems and the design criteria developed by the NRC and DOE for terrestrial nuclear systems. However, those techniques (i.e., the details underlying these foundations) will need to be reviewed and may need modification to address aspects of space fission reactors, owing to the very different constraints for which they will be designed and operated, e.g., minimizing of payload weight, heat rejection in a vacuum, NSPM-20's potential radiological accident probabilities and consequences, and differing accident environments, when addressing inadvertent re-criticality.

II. ASSESSING AGENCY NEEDS

Each of the seven agencies participating have varying roles in the lifecycle of a space fission reactor system. These roles include design, development, testing, transportation, licensing, certification, launch approval, protection of human health and the environment, launch site management, reactor operations, and ultimate disposal. Some agencies have multiple roles, depending on the mission. Each agency provided a list of potential standards needs and the SWG determined that these fall into two categories: process needs and specific technical needs. In the list given here, the specific agency needs (bullet items) have been grouped into high-level needs (the numbered items).

1. Safety Design Process for Space Nuclear Reactors – the factors that need to be considered and addressed in a new space reactor design.
    - Process-focused materials that are consistent with the other agencies that are involved.

2. General Design Criteria for Space Nuclear Reactors – specific design requirements that all space reactors should meet.
    - Mission performance criteria to justify use of HEU in space reactors.
    - Definition of environments for which space reactors and reactor fuel must remain subcritical.

- Design reactivity margins for achieving criticality in space reactors.
- Design reactivity margins for maintaining subcriticality in space reactors.
- Criteria for inadvertent criticality.
- Methods to verify design life of space reactors.
- Minimum factors of safety for space reactor pressure vessels.
- Criteria for space reactor configuration during reentry (i.e., how to evaluate burnup vs. intact vs. scattered reentry choices).
- Resiliency.
- Criteria for when space reactors can be started up.

3. Storage of Test and Flight Space Reactors – safety requirements for storing assembled or disassembled reactors at test sites, launch facilities and other locations.
   - Criteria for storing test and flight space reactors.
   - Transportation/storage of nuclear equipment on ground.

4. Transportation of Test and Flight Space Reactors – safety requirements for transporting space reactors and nuclear equipment between and within facilities.
   - Transportation/storage of nuclear equipment on ground.
   - Criteria for transporting test and flight space reactors.
   - Transportation standards for transportable reactors.

5. Testing Requirements for Space Reactors – ground test requirements for new reactors prior to their use in space.
   - Pre-flight verification testing standards for flight space reactors.
   - Ground nuclear testing standards to qualify space reactor designs.
   - Testing standards for factory-built systems.
   - Space reactor testing requirements different from ground reactors.

6. Facility Requirements for Testing – requirements for facilities to appropriately simulate anticipated environments.
   - Criteria for impacts of ground safety systems on space reactor testing, including impacts on the goal of test-as-you-fly.
   - Requirements for propulsion tests (i.e., how to meet federal public health and environmental regulatory requirements).
   - Simulation of space environments.

7. Flight Certification or Licensing Process Requirements – requirements for launch safety and integration with launch and spacecraft systems. *(Note that the terms 'certification' and 'licensing' often take on specific meanings, which vary between departments and agencies. In this paper, these terms are used generally and not precisely, and should not be confused with specific definitions within any particular organization.)*
   - Process focused materials that are consistent with the other agencies that are involved.
   - Launch safety.
   - Flight certification (i.e., how to certify and how to treat nuclear payloads).

8. Safety and Risk Analysis Methods – requirements for risk analysis methods for performing NSPM-20 and related calculations.
   - Methods to calculate the potential accident probabilities versus maximum dose levels stipulated in NSPM-20.
   - Processes to analyze other aspects of launch authorization.
   - Methods for analyzing risks from inadvertent reentry.

9. Methods to Calculate Radiation Doses from Space Reactors – requirements for assessing astronaut safety and shielding needs.
   - Methods to account for operating reactor systems on crew dose assessments (shielding and doses from other sources).

10. Safe Operating Practices for Space Reactors – requirements for operating reactors during all planned operational phases.
   - Fault-tolerance strategies for space reactor startup and shutdown.
   - Considerations for space reactor operational controls (i.e., how to implement autonomous and manual controls).
   - Instrumentation and telemetric data rate expectations for space reactors.
   - Operating guidance for nuclear systems in space.
   - Guidance for proximity operations and on-orbit servicing.
   - Planetary protection issues.
   - Resiliency.

11. Decommissioning and Disposal of Space Reactors – requirements for safe end of life decommissioning and disposal.
   - Process-focused materials that are consistent with the other agencies that are involved.
   - De-commissioning guidance for systems in space
   - Environmental contamination criteria for space disposal.
   - Methods to comply with Space Policy Directive 6 (e.g., sufficiently high orbit and sufficient radioactive decay).[4]
   - Interim storage and ultimate disposal of ground test reactors and used fuel.

The high-level needs identified above were determined to not be sufficiently met for space reactors by available guidance/standards and are therefore considered to be gaps. It is important to note that all gaps do not have to be addressed by consensus technical standards. Other means, such as agency developed practices, procedures or handbooks can be utilized.

II.A. Criteria for Prioritizing Standards Gaps

The SWG developed a set of criteria for evaluating gaps to determine whether each was appropriate for future consideration by the SWG and, if so, how to prioritize them. Four required criteria were identified. If an identified gap did not meet any of those criteria, it was removed from further consideration. The SWG identified seven desired criteria to determine relative priorities of each gap.

<u>Required Criteria</u>

1. The gap applies to multiple agencies.

   If the gap applies to only a single agency, then it could potentially be addressed by internal agency standards and guides.

2. The gap can be addressed by a standard.

   In some cases, the gap may be dominated by policy issues. In other cases, the gap may be ill-defined or rapidly evolving such that a standard is not appropriate.

3. An existing standard is not available to all agencies to meet the gap.

   Existing standards should not be duplicated by this effort. No cases were identified where existing standards filled the identified gap.

4. The gap is associated with space fission reactor design or safety.

   This criterion was used to limit the scope of the activity. Radioisotope or exotic power systems were excluded, along with issues not related to design or safety, such as manufacturing, economics, or project management.

<u>Desired Criteria</u>

1. A standard would reduce costs and/or delays in the approval process.

   Successful standards tend to be those where there is an incentive for their use. Done properly, a standard can resolve controversial issues and reduce uncertainty in the approval process.

2. A standard would result in more consistent treatment of nuclear safety across agencies.

   Public health and safety should be independent of the government agency involved. Consistency can help prevent designers from "shopping" their ideas with different agencies looking for the easiest approval process.

3. A new standard may help resolve conflicts among existing standards.

   Where different agencies may be involved in design, launch and operation of a space reactor, it is possible that different rules may come into conflict. Consensus standards can help eliminate those conflicts.

4. The gap is not technology specific.

   In the future, detailed technology-specific standards may be developed. However, such standards are premature at this time, and the development of standards should not favor a particular technology during this early development phase.

5. The gap does not favor a particular designer or contractor, including government sponsored versus commercial.

   Similar to criterion #8, standards should not be developed that would tend to favor a particular organization over others.

6. The technical basis for a standard exists.

   Standards are often written based on long-standing practice and experience. This is not the case for space reactors. However, expertise exists in the design and safety analysis of nuclear space systems, including reactors. In cases where expertise is limited, standards are sometimes developed for trial use, and endorsed later for widespread use. In some cases, there may be existing standards that can be modified for use with space reactors. This criterion assesses whether there is enough technical expertise and background information available to proceed.

7. The standard can be completed in a reasonable time.

   Standards are often a multi-year process. If a standards activity cannot be defined on a schedule that is reasonable given the need, then the standard should not be pursued

The criteria were used by each agency to prioritize identified gaps. The criteria were applied subjectively by each agency, and no weighting was assumed. After an initial round of ranking, the SWG discussed the gaps and

how they applied the criteria, which led to the results discussed below.

II.B. Results of Prioritization

As seen above, the SWG initially identified a list of 42 potential standards needs that were consolidated into 11 high-level needs, which were subsequently identified as gaps. The SWG decided that some gaps should be combined with others in the list before further consideration and prioritization began. The SWG then discussed prioritization for the remaining gaps into High, Medium, and Low categories. High-Priority Gaps have a strong possibility for consideration to move on to standard development. Medium-Priority Gaps could be moved on to consensus standard development if they become more fully established, but with a significantly lower need at this time. Low-Priority Gaps should not be considered as part of this effort to progress into a standard development process at this time but could be important topics for consideration by individual agencies through internal process documents or best-practice handbooks. It is important to note here that where a particular gap falls on the list currently is not a reflection of its potential importance. The SWG was not tasked with creating broad judgements, but rather was focused on whether any gap is sufficiently important to be recommended to a consensus standard committee. Following the identification of the 11 primary gaps, discussion centered on reducing the number of gaps for final consideration by combining similar gaps with others.

The three gaps that were combined with others were:

- Gap #4 - Transportation of Test and Flight Space Reactors was combined with Gap #3 - Storage of Test and Flight Space Reactors, because the activities related to the transportation and storage of test and flight reactors were determined to be similar enough to each other that they could be combined into one more concise collective gap.
- Gap #6 – Facility Requirements for Testing was combined with Gap #5 - Testing Requirements for Space Reactors into Testing Requirements for Space Reactors, including Facility Requirements, because the facilities required for testing would be an integral part of the overall testing program and did not need to be considered as a separate gap with respect to the work of this SWG.
- Gap #9 - Methods to Calculate Radiation Doses from Space Reactors was combined with Gap #10 - Safe Operating Practices for Space Reactors, because the methods used to determine the direct radiation doses from space reactors are well understood and can be justifiably considered to be part of the determination of how to safely operate and work in the vicinity of space reactors.

After considerable discussion, Gaps #5, #8, and #10 were categorized as High importance, with Gap #8 ranking the highest.

- Gap #5, Testing Requirements for Space Reactors, including Facility Requirements was highly rated due to the perceived need to have guidance available on what testing can and should be conducted. Testing that would benefit greatly from standardization includes ground testing of components and full systems, pre-flight testing, launch preparation testing, pre-start testing and others.
- Discussion around Gap #8 concerning Safety and Risk Analysis Methods centered on standardization and maturity for this application of the methods and techniques used to analyze safety and risk. These analysis techniques appear to be well founded in their applications to other technologies, i.e., terrestrial reactors, probabilistic risk assessments, and others, and this area would be appropriate for the development of relevant consensus standards that support meeting the requirements of NSPM-20.
- The discussion of Gap #10 regarding the development of Safe Operating Practices for Space Reactors concentrated on observations that this area could be ready for consensus standard development. The identification of the choices of methods and analytical approaches seem to be well founded and available. This would include the methods and techniques used to calculate radiation doses from space reactors and the understanding of operational principles and practices of other nuclear reactors and their systems over the past five decades.

There are two gap areas that were determined by the SWG to fall within the Medium/Low Category, namely Gaps #3 and #11. Both gaps were of considerably less importance for moving directly into a consensus standards process. However, again, this does not imply that they should not eventually be considered in the future, just that they were of considerably lower initial priority as determined by the SWG.

- Gap #3, the Storage of Test and Flight Space Reactors, was determined to be not quite ready for consensus standard committee development at this time. It was discussed that too little was currently known about the individual designs of space reactors and there was too much variability in the applications of these designs to be able to

appropriately develop effective consensus standards in this area.

- Also following a similar vein of conversation, Gap #11, the Decommissioning and Disposal of Space Reactors, was determined to not be ready for consensus standard development at this time. This will certainly need to be part of the discussion leading to a determination on the decommissioning and disposal of every reactor considered for use in a space mission; however, presently there remain too many variables (mission objectives, mission design, flight paths, operational envelopes, etc.) to be considered for the identification of effective consensus standards in this area.

Three gaps were identified in the Low Category, specifically Gaps #1, #2 and #7. Each of these gaps was deemed to not be currently ready or appropriate for consensus standard development. However, it will be important for one or more of the relevant agencies to focus on the further development of all three of these gaps at some point in the future, possibly through the development of an agency specific standard or handbook. Specifically:

- Discussion about Gap #1, Safety Design Process for Space Nuclear Reactors, was centered around the maturity of space reactor designs to enable the development of such a standard at this time.
- Gap #2, General Design Criteria for Space Nuclear Reactors, may not be technology-neutral enough at this time to enable a consensus standards committee to adequately establish a consensus standard in this area.
- Gap #7, Flight Certification or Licensing Process Requirements does not at this time appear fully developed enough to consider for passing on to a consensus standards committee.

Table I provides a summary of the results of these discussions and characterizes the final ranking of the 11 primary gaps.

III. CONSENSUS FINDINGS AND RECOMMENDATIONS

The SWG believes that this study has been valuable and has identified important gaps where consensus technical standards can add value and should be pursued. The SWG has allowed relevant federal agencies to exchange ideas about the future of consensus technical standards as they apply to space fission reactor systems. All seven agencies play a role in some aspect of the space reactor system lifecycle.

Table I. Results of Prioritization of Gaps.

Gap Number	Title	Rank
1	Safety Design Process for Space Nuclear Reactors	Low
2	General Design Criteria for Space Nuclear Reactors	Low
3	Storage of Test and Flight Space Reactors	Med/Low
4	Transportation of Test and Flight Space Reactors	Subsumed into #3
5	Testing Requirements for Space Reactors, including Facility Requirements	High
6	Facility Requirements for Testing	Subsumed into #5
7	Flight Certification or Licensing Process Requirements	Low
8	Safety and Risk Analysis Methods	High
9	Methods to Calculate Radiation Doses from Space Reactors	Subsumed into #10
10	Safe Operating Practices for Space Reactors	High
11	Decommissioning and Disposal of Space Reactors	Med/Low

The SWG identified four specific findings related to this study:

1. Consensus standards have value and should be pursued for space reactors.
2. An extensive review was conducted, and a list of relevant existing standards was compiled that should be a resource for future efforts.
3. Gaps that were not prioritized for near-term action are still considered important and could be topics for future agency-level guidance documents or community-of-practice workshops among member agencies to resolve the differences in the perceived gap significance.
4. The process used for standards development would benefit from broad participation by government agencies, stakeholders, consensus body organizations, industry, and academia.

The SWG also made the following specific recommendations:

1. The three gaps identified as high priority should be pursued through a consensus standards development process in the near term, namely:
   - Safety and Risk Analysis Methods for Space Reactors.
   - Testing Requirements for Space Reactors, including Facility Requirements.
   - Safe Operating Practices for Space Reactors.
2. An agency should be identified as the "champion" for each of the three gaps to develop a work plan to define the next steps for each gap (including expected cost and schedule) and engage other agencies and the appropriate consensus standards organizations, as appropriate.
3. NASA should convene an interagency group periodically to review progress.

IV. CONCLUSIONS

An interagency space reactor standards working group was convened to address the lack of formalized processes to guide space reactor development and mission use. The findings and recommendations of the SWG were presented to the agency Standards Executives. The next steps were put in motion to establish "champion" agencies for each of the three gaps and to engage the appropriate standards organizations.

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DISCLAIMER

Personnel from federal regulatory organizations participated in the space reactor standards working group at the request of their agency Standards Executives. No US Government agency endorses or rejects the conclusions of this paper. This paper should not be construed as a rule, policy, means of compliance, guidance statement, or an interpretation of such.

REFERENCES

1. Presidential Memorandum on Launch of Spacecraft Containing Space Nuclear Systems, The White House, NSPM-20, August 20, 2019.
2. Federal Participation in the Development and Use of Voluntary Consensus Standards and in Conformity Assessment Activities, OMB Circular No. A-119 Revised, February 10, 1998.
3. Principles for Federal Engagement in Standards Activities to Address National Priorities, White House, M-12-08, January 17, 2012.
4. Memorandum on the National Strategy for Space Nuclear Power and Propulsion, Space Policy Directive 6, The White House, SPD-6, December 16, 2020.